Issues in Disk-laser Key-hole Welding of 2024 Aluminum Alloy

A Comprehensive View about Process and Joint Quality Improvement

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Abstract

Many issues are involved in laser welding of any kind of aluminum alloy, in addition to typical ones addressed when considering conventional welding techniques. The aim of this paper is to give a comprehensive view about key-hole related dynamics as well as possible ways to enhance joint quality in disk-laser welding of 2024 aluminum alloy.

Keywords

Aluminum Alloy; Laser Welding; Disk-laser; Porosity; Key-hole

Introduction

Higher productivity, lower distortion and better penetration are achieved by laser beams as heat source for welding in comparison with conventional techniques. Nevertheless, to benefit from these advantages, specific issues are required to be addressed depending on the material to be welded.

Since weight reduction is one of the most effective ways to enhance efficiency and improve fuel mileage in vehicles and aircraft, aluminum alloys are increasingly being used both in automotive and aerospace industries [1], thanks to excellent mechanical properties as well as resistance to corrosion [2, 3]. Among all them, 2024 aluminum alloy is widely common; its chemical composition is shown in Table I. Copper is generally added to increase strength following solution heat treatment and quenching; as little as approximately 0.5% Magnesium is effective in changing aging characteristics [4].

Key-hole welding is generally preferred because high aspect ratios and narrow heat affected zones are produced. However, a key-hole may oscillate and close intermittently causing porosity due to gas entrapment [5]. Several studies about aluminum welding with laser sources already pointed out the need for proper gas supply systems to both prevent oxidation and blow the metal plume away from the welding area [2, 6, 7], since vapors escaping from the key-hole may shield the beam, such that improper or incomplete fusion of the base material would result. Indeed, energy delivering to adequately melt the abutting surfaces is hindered by low aluminum absorptance to laser wavelength and high thermal conductivity [4]. Furthermore, when aiming to produce fully penetrative welds, key-hole instability has been addressed as reason for macro pores [8, 9, 10] and hence bead rejection at quality checks. New processing methods such as oscillation welding [11] and laser-arc hybrid welding [12] have been suggested to improve the aluminum laser weldability.

TABLE 1 AA 2024 NOMINAL CHEMICAL COMPOSITION (WT. %)

Cu	Mg	Mn	Si	Fe	Cr	Zn	Ti	Al
3.80÷4.90	1.20÷1.80	0.30÷0.90	0.50	0.50	0.1	0.25	0.15	Bal.

Main issues in laser welding of AA 2024 are discussed in this paper. The experimental results were obtained using a Trumpf TruDisk 2002 Yb:YAG disk-laser; the beam was delivered to a Trumpf BEO D70 welding head, moved by an ABB IRB 2400/16 robot. Welding system technical data are listed in Table II.

TABLE 2 WELDING SYSTEM TECHNICAL DATA

Laser maximum output power [kW]	2.0
Laser light wavelength [μm]	1.03
Beam parameter product [mm × mrad]	8.0
Focal length [mm]	200
Fiber diameter [mm]	0.3
Focal spot diameter [mm]	0.3

Specific advantages are benefited by employing disk-laser sources in aluminum welding [13]: better concentration of the energy to melt the base material

in a key-hole shaped and fully penetrative weld is achieved because of low divergence [14] which also reduces the extent of both the fused zone and the heat affected zone (HAZ) whose mechanical properties are lower than the properties in the base metal.

Gas Supply

A gas flow impinging the laser focus from the side is a common feature in laser welding systems [15]. Two roles are accomplished: protection of the weld pool to prevent oxidation during the process, and removal of plasma consisting in high-temperature thermally excited vapors [16], resulting from metal vaporization in key-hole welding conditions, which may produce unplanned beam defocusing [1]. Many studies dealt with plume generation and process stability in welding aluminum alloys; both the physical properties of the gas and nozzle geometries were considered [2, 6, 7]. The gas jet set-up is a carryover from usual practice for welding steel, so copper nozzles are placed with 30÷60° tilting angle with respect to the metal surface [1]. The choice of gas flow is connected to the stability of welding process, as in certain conditions it can affect the dynamic behaviour of the key-hole [17]. Previous works showed that argon upper shielding produces less absorptance due to plasma interaction, whilst better results were achieved using helium [2, 13], because it has a higher ionization potential such that better process stability and optimal coupling of the beam with the metal surface [1, 14] are benefited. In addition, finer spatter droplets were produced compared to argon [2]. Convincing results were achieved in this study using a 25° tilted trailing nozzle; a helium flow at a rate of 15 l/min provided both shielding and plasma blow.

A proper time delay was set before welding to prepare inert atmosphere on the joint and provide stable shielding flow; additional time was required to effectively shield the bead after laser switch-off.

In addition, back-side shielding was provided to protect the bead root in fully penetrative welding. A specific device is here suggested: the plates are clamped on a grooved box which injects the shielding gas on the lower surface of the joint. Argon can be effectively used for this purpose because there is no interaction between the laser beam and the back-side shielding flow. Furthermore, additional gas flow supply was required to protect the optics from possible molten metal spatters which are quite common when welding aluminum alloys. Hence, a high speed compressed air cross-jet was blown at the laser beam exit, at a proper height which would not interfere with gas shielding. A scheme for the suggested set-up is shown in Figure 1 and was successfully tested to weld AA 2024 in different thickness samples [13, 14, 21] in BOP, butt and overlapping configuration.

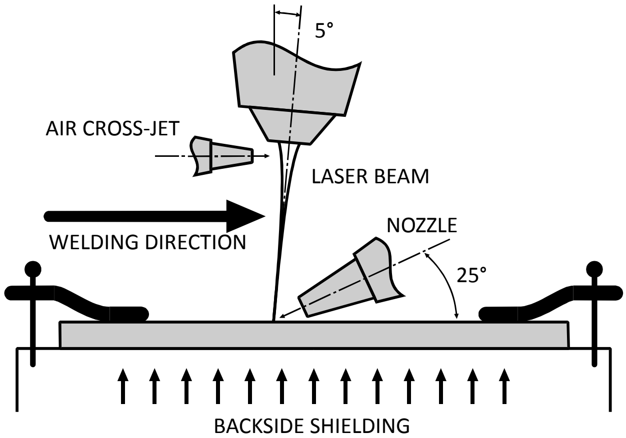

FIG. 1 SUGGESTED WELDING SYSTEM SET-UP

General Issues in Laser-Material Interaction

One of the main reasons of incomplete fusion of the base material is the possible presence of natural oxide on the plates. Aluminum has indeed strong chemical affinity for oxygen and therefore it oxidizes immediately upon exposure to air: aluminum oxide melts at approximately 2050 °C, which is much higher than the melting point of the base alloy which is roughly 600° C, so any oxide on the abutting surfaces needs to be properly removed [2, 4], as well as any source of foreign material which could produce inclusions in the bead. Since adequate joint preparation is deemed to be vital for sound beads, it is recommended to clean both sides of the joint when preparing surfaces for deep penetrative welding.

High thermal conductivity and low absorptance are further issues to be addressed. Although the melting temperature of aluminum is lower compared with any ferrous alloy, irrespective of the alloying elements, higher specific energy per volume is required to effectively melt aluminum due to its higher reflectivity, which ranges between 0.86 and 0.90 for pure aluminum at laser wavelength between 0.9 and 1.0 μm [18]; aluminum reflectivity as a function of laser wavelength [19] is shown in Figure 2.

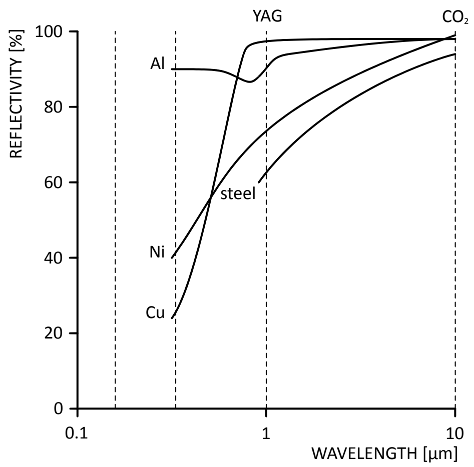

FIG. 2 REFLECTIVITY OF A NUMBER OF METALS AS A FUNCTION OF LASER WAVELENGTH

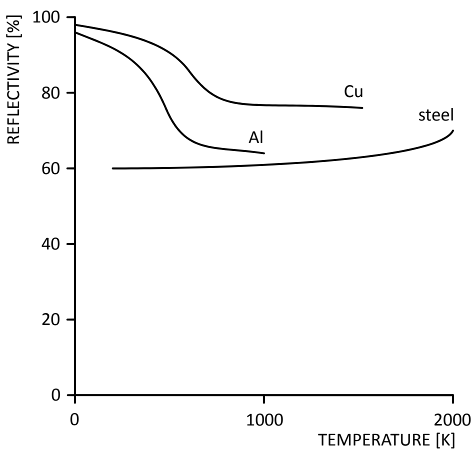

FIG. 3 REFLECTIVITY AS A FUNCTION OF TEMPERATURE FOR YAG RADIATION

The purer is the alloy, the higher is the reflectivity [18]. Nevertheless, absorptance may be enhanced in a variety of factors [13]; in particular, reflectivity is a function of the thermal state of the material and, as shown in Figure 3, it decreases as temperature increases [19]. As an example, the result of a bead-on-plate (BOP) test on 3.2 mm thick plate is shown in Figure 4: with a power of 1.2 kW and a speed of 6 mm/s in focused condition, fusion was not produced at the beginning of the welding path whilst a key-hole mode welding condition started when reflectivity decreased during the process as a consequence of heating [21]. In order to allow the key-hole to develop since the start of the welding path when considering a butt joint configuration, a threshold value of approximately 18.4 kW/mm^2 specific energy input has to be overcome [21]. Reflectivity is an issue which demands specific changes in the normal processing set-up anyway.

Therefore, in order to prevent damages to the focusing optics and the cavity, due to back reflection prompted by low aluminum absorptance, a sideways tilting angle, in the order of degrees, was used to position the laser welding head [21]. It was found that an entry welding spot, provided before welding at the beginning of the welding path to better tighten the samples and prevent slippage during melting, also reduces locally the reflectivity so that fully penetration was enhanced [22].

FIG. 4 INCOMPLETE KEY-HOLE DEVELOPMENT ON 3.2 MM THICK SAMPLE, 1.2 KW POWER LEVEL, 6 MM/S WELDING SPEED IN FOCUSED CONDITION

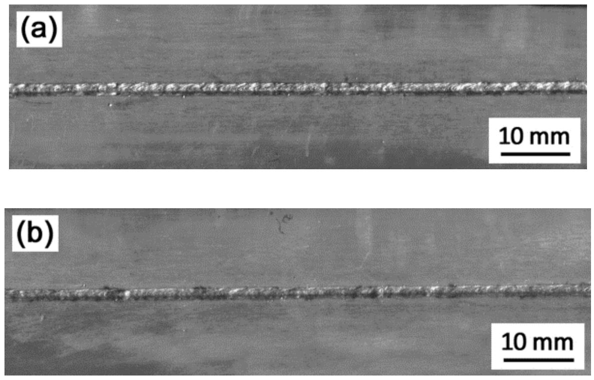

FIG. 5 BEAD ASPECT FOR 1.25 MM THICK SAMPLE, 1.6 KW POWER LEVEL, 60 MM/S WELDING SPEED IN FOCUSED CONDITION; (A) TOP-SIDE AND (B) BACK-SIDE APPEARANCE

In addition to low absorptance, energy transfer from the beam to the material is further worsen as a consequence of higher thermal conductivity of the base metal which is of 120 W/mK in the case of AA 2024, so six times greater compared to steel. Higher heat inputs and irradiance are hence required. Due to its high thermal conductivity, and irrespective of the heating source, aluminum is very sensitive to fluctuations in heat input during the welding process whilst a steady input is required to avoid variation in penetration and fusion [4]. However, the high specific energy provided with laser sources allows using higher welding speed, therefore the total processing time is shortened and both the upper crown and the lower root of the beam are found constant along the welding line. The upper and lower surfaces of AA 2024 butt welded beads are provided in Figure 5, for 1.25 mm thick samples processed with a power of 1.6 kW power level, a speed of 60 mm/s in focused condition.

Porosity Evolution

Two types of porosity arise when welding aluminum. Micro pores, whose mean diameter ranges between 50 and 200 μm [8] do not normally result in the rejection of welded parts: they are ascribed to hydrogen and other common gases which are released and trapped in the solidifying alloy because their solubility in liquid metal is significantly higher compared to the solubility in the solid state [9, 10]; the hydrogen that exceeds the effective solubility limit and does not escape from the solidifying weld then forms gas porosity [4].

Macro pores, instead, whose size ranges between 300 and 600 μm, seriously affect mechanical properties of the welding bead and therefore are worth investigating. They are due to imperfect collapses of the key-hole during welding and are common in any type of aluminum alloy as a consequence of large differences in boiling and melting points of the base metal and the main alloying elements, as shown in Figure 6 for the alloy under examination. In particular, high magnesium content favors gas occlusions and non-stable key-holes for AA 2024 [8, 14].

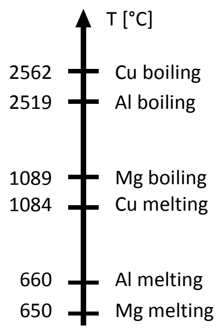

FIG. 6 BOILING AND MELTING POINTS OF MAIN ALLOYING ELEMENTS IN AA 2024

Magnesium vaporization during welding thermal cycles affects the macro porosity content; it is inferred that a change is produced in the key-hole pressure balance equation, since ablation is a non equilibrium process [17]. The loss in magnesium content, and therefore the final amount of porosity, depends on processing parameters and was clearly noticed via energy dispersive spectrometry (EDS) analysis in the transverse cross-section of the bead. An average loss of magnesium in the order of 53% was estimated when butt welding 3.2 mm thick plates with a power of 1.6 kW, a speed of 10 mm/s and 0.5 mm of negative defocusing [14]. Magnesium content as a function of the distance from the welding axis of the bead is shown in Figure 7: it decreases moving from the base metal, where a nominal reference value of 1.56% was detected on average, towards the fused zone.

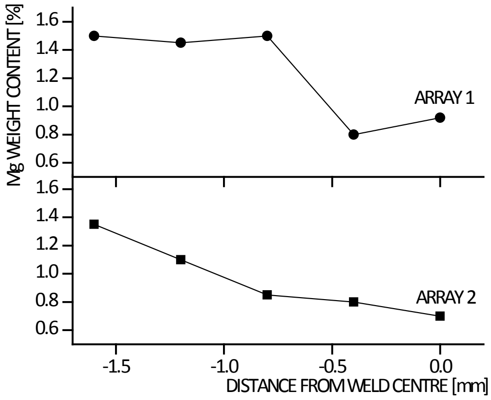

FIG. 7 MG CONTENT IN CROSS-SECTION; 3.2 MM THICK PLATES, 1.6 KW POWER LEVEL, 10 MM/S WELDING SPEED, 0.5 NEGATIVE DEFOCUSING

Magnesium concentration for site of interests in the bulk of the weld metal was uniform, thus suggesting that vigorous convective mixing occurs in the molten metal as key-hole develops.

Higher welding speeds and lower heat inputs must be used to match the quality requirements when welding 1.25 mm thick sheets of the same alloy. Magnesium content as detected via EDS analysis is shown in Figure 8 for a butt welded specimen processed with a power of 1.6 kW, a speed of 80 mm/s in focused condition [13]. A 1.16% residual magnesium content was measured in the bulk of the welded metal. Vaporization of the alloying elements was lower due to shorter interaction period between laser and material, so the process was conducted in much more stable condition. No macro porosities were detected indeed in random cross sections.

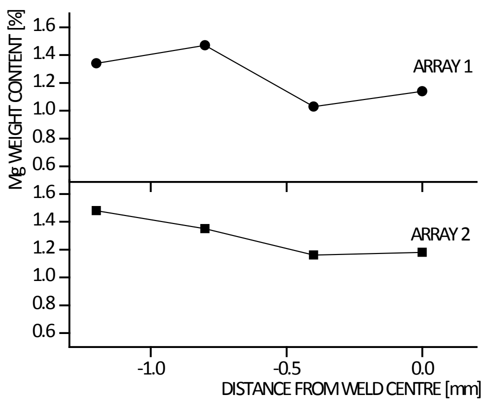

FIG. 8 MG CONTENT IN THE CROSS SECTION; 1.25 MM THICK SHEET, 1.6 KW POWER LEVEL, 80 MM/S WELDING SPEED, FOCUSED CONDITION

Thermal input dependence

Macro porosity evolution depends on the welding conditions. A significant influence is due to thermal input, i.e., the laser power to welding speed ratio. Longitudinal sections of two 3.2 mm thick butt welded specimens obtained with 160 and 200 J/mm thermal input are shown in Figure 9. Provided that fully penetrative conditions are accomplished, lower thermal inputs resulted in increasing porosity. From measurements in the longitudinal sections, the average amount was close to the limit of 5% porosity content with respect of the total fused zone, which is allowed by international specifications [23], so welding was carried out in critical conditions which would easily result in bead rejection at quality checks. An amount of 15% porosity content was observed with much lower thermal input of 80 J/mm [22].

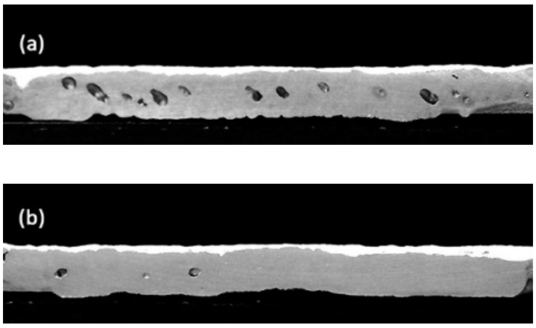

FIG. 9 LONGITUDINAL SECTIONS OF 3.2 MM THICK SAMPLES, PROCESSED WITH (A) 160 J/MM AND (B) 200 J/MM THERMAL INPUT

The material flow in the melted pool has a vortex structure whose convection patterns start from the top of the weld surface, ending towards the tip of the key-hole [19] thus resulting in bubble ejection in fully penetrative welds. The process is enhanced when higher thermal input is provided [21]. Conversely, it is inferred that higher thermal input in incomplete penetrative welds do only enhance vaporisation of elements such as magnesium which favours key-hole instability and gas occlusions.

Defocusing effect

There are suggestions that, as for any metal alloy, defocused laser beam can improve the quality in aluminum joints in term of porosity content and enhanced penetration depth [8, 9, 10]. To weld in defocused conditions, the beam focus point needs to be located inside or outside the upper surface of the plates to be welded, thus producing negative or positive defocusing, respectively. Because a change results in the specific energy provided and in the fused zone extent, a different material response is expected [14].

The effects of different focal positions were studied on 3.2 mm thick plates in butt configuration. Once the 18.4 kW/mm^2 threshold value was provided with a fixed power of 1.8 kW and a welding speed of 10 mm/s, a key-hole mode developed with 1 mm of negative defocusing, because the focal position located within the material; conversely, 1 mm of positive defocusing only melted the surface and no key-hole mode developed, because the beam expanded through the material and specific energy decreased along the propagation axis, although disk-laser divergence was considered to be low [14]. The outcome suggested that even though a laser beam is symmetrical around its waist, different material responses are achieved when the same defocusing shift is set in positive or in negative direction. To further discuss this behaviour, porosity content trend as a function of focus position is shown in Figure 10; a power level of 1.8 kW and a welding speed of 10 mm/s were taken as constant.

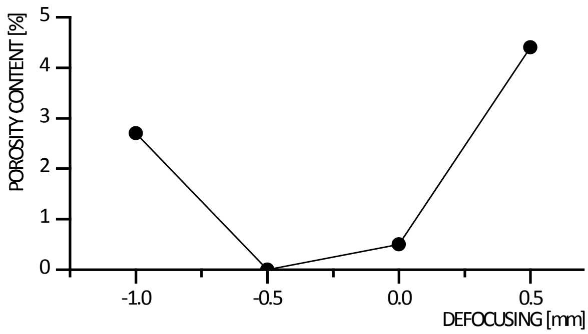

FIG. 10 POROSITY CONTENT AS A FUNCTION OF DEFOCUSING; 3.2 MM THICK SAMPLES, 1.8 KW POWER LEVEL, 10 MM/S WELDING SPEED

When positive defocusing to 0.5 mm, the resulting porosity content was due to incomplete penetration, since whirling patterns in the fused material did not reach the lower surface and therefore bubble ejection was hindered. On the other hand, a reduction was achieved when negative defocusing to 0.5 mm, compared to focused conditions. Nevertheless, when further negative defocusing to 1 mm, the pressure terms in the balance equation are affected, moving the stable solution for the equilibrium radius of the key-hole [17]. To support the assumption, cross-section with 10 mm step is shown in Figure 11: the bead shape was clearly irregular along the welding direction and macro pores were found in the cross-section. This is enough to assess that AA 2024 is highly susceptible to minimal deviation of the focal position.

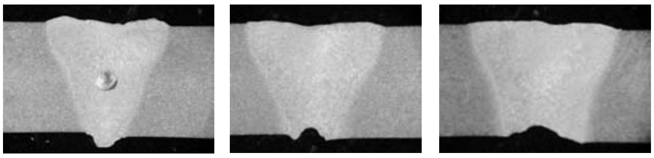

FIG. 11 BEAD CROSS-SECTION WITH 10 MM STEP ALONG THE WELDING DIRECTION

3.2 mm thick samples, 1.8 kW power level, 10 mm/s welding speed; 1 mm negative defocusing

Softening In the Fused Zone

Laser welding thermal cycles with rapid heating and cooling result in changes in the material structure. A micrograph of the cross-section of a 3.2 mm thick butt welded specimen obtained with a power of 1.8 kW and a speed of 20 mm/s in focused condition is shown in Figure 12. Dark particles in the base material are $Cu_2Mn_3Al_{20}$, $CuMgAl_2$ and Cu_2FeAl_7 precipitates [4] resulting from preliminary solution heat treatment and room temperature ageing, as 2024 in T3 state is considered; columnar growth of the grains in the direction of thermal gradients was observed in the fused zone.

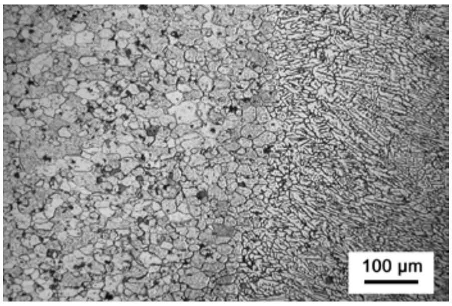

FIG. 12 MICROGRAPH IN THE BEAD CROSS-SECTION: BASE MATERIAL ON THE LEFT; WELDING BEAD ON THE RIGHT

A heat affected zone (HAZ), i.e., any fraction of metal which has not been melted, but whose mechanical properties or microstructure have been altered by the heat source of welding, is supposed to exist between the base metal and the bead. Furthermore, AA 2024 is specifically susceptible to softening in the fused zone as a consequence of precipitates dissolution [4]. The effect is commonly referred to as HAZ and fused zone degradation. When temperatures in the HAZ exceed the solvus curves, respective phases are dissolved. At a position which is close to the fusion zone, higher temperatures are experienced and greater dissolution of strengthening phases occurs.

A common method to assess the extent of the HAZ and highlight the effects of the laser welding cycles in softening the fused zone is micro hardness testing in the transverse bead cross-section. Vickers indentations were hence made with 0.98 N (i.e., 0.1 kgf) load for 15 s at a speed of 60 μm/s; tests were performed one week after welding in order to allow the stabilization of material properties during its average period of natural ageing [4].

Micro hardness trend as a function of the distance from weld centre is shown in Figure 13 for indentations at mid-thickness: as expected, a decrease in micro hardness is noticed from 145 $HV_{0.1}$ in the base metal to average 105 in the fused zone. No transition values were observed between the zones, so it was not possible to assess the HAZ extent; nevertheless, the HAZ extent was assumed to be less than the distance between two consecutive indentations, i.e., 150 μm according to the reference standard [24]. Interestingly, when welding 3.2 mm thick samples with higher thermal input, no differences in micro hardness values and trend were found, thus suggesting that any decrease in material properties was basically the result of a threshold point for precipitates dissolution being overcome, irrespective of the welding parameters.

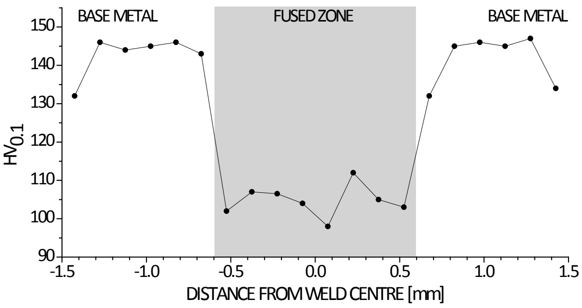

FIG. 13 VICKERS MICRO HARDNESS TREND IN THE CROSS-SECTION; INDENTATION AT MID-THICKNESS; 1.4 KW POWER LEVEL, 80 MM/S SPEED, 0.5 POSITIVE DEFOCUSING

Anyway, longer interaction between metal and heat source affect the HAZ extent which, for example, ranges from 200 to 250 μm for a butt welded specimen obtained at 1.6 kW power level and 10 mm/s welding speed in focused conditions [22].

As a consequence of degradation in the fused zone, fracture was expected to have place in the bead whose mechanical features are lower compared to those ones in the base metal. It is widely accepted in several researches about different aluminum alloys [3, 25, 26] that any welding bead showing an ultimate tensile strength (UTS) higher than the 66% of the base material is acceptable.

Optimization of the laser welding process on 1.25 mm thick sheets, basing on systematic approach involving

geometry checks and non destructive tests, suggested a power of 1.4 kW, a speed of 80 mm/s with 0.5 of positive defocusing as the optimal condition to weld 1.25 mm thick sheets. To eventually assess the joint mechanical quality, three specimens were milled from three independent welding beads in accordance with UNI EN ISO 4136:2011 [27], and then loaded in a direction perpendicular to the welding bead, hence tested with a crosshead speed of 0.015 mm/s. Percent elongation at break and UTS resulting from the tensile tests are listed in Table III; UTSs are also compared to UTS_0 reference value, i.e., 480 MPa for the original and non welded sample, as expected from the material data sheets [4]. An average value of 370 MPa (77% of the UTS of the base material) resulted. Cracks in each tested specimen started from the weld and grew towards the interface between weld and base material, where steep discontinuity was experienced in crossing zones as shown in the micro hardness analysis. Top- and back-side crack surfaces are shown in Figure 14.

TABLE 3 PERCENT ELONGATION AT BREAK AND UTS FROM TENSILE TESTS

Test	UTS [MPa]	UTS/UTS_0 [%]	Elongation [%]
1	385	80	1
2	369	77	1
3	357	74	1

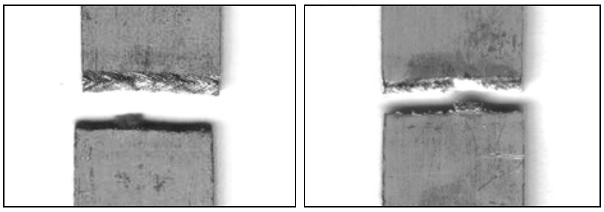

FIG. 14 CRACK SURFACES FROM TENSILE TESTS: (LEFT) TOP-SIDE, (RIGHT) BACK-SIDE

Conclusions

Laser-related issues in welding 2024 aluminum alloy were discussed in this paper. A scheme to shield the bead and blow the metal plume was been suggested, consisting in a trailing tilted nozzle with air cross-jet flow; the laser beam was delivered with 5° angle to avoid back reflections due to low aluminum absorptance. Clear advantages in coupling the laser beam with the base metal were achieved when shielding with helium compared to argon.

Proper joint preparation is required in order to remove aluminum oxide and any foreign material which may produce inclusions in the bead. The need of a threshold value of approximately 18.4 kW/mm² specific energy input was found, due to high thermal conductivity and low absorptance at laser wavelength. Both the thermal input and the defocusing effects were discussed as a way to improve joint quality in terms of lower macro porosity content. The issue relates to magnesium loss during welding thermal cycles, as a decrease in magnesium concentration was found via energy dispersive spectrometry, moving from the base metal towards the fused zone in the cross-section. Higher thermal inputs in fully penetrative welding conditions were found to be appropriate to enhance convective vortex structure in the fused zone, thus easing bubble ejection; defocusing was proven to be decisive in moving the key-hole stable condition, although AA 2024 is highly susceptible to minimal deviation of the focal position. As a consequence of rapid heating and cooling, dissolution of strengthening precipitates occurred in the bead and the heat affected zones, so a decrease in Vickers micro hardness values resulted in the bead. Nevertheless, when tensile testing the welded samples, convincing ultimate tensile strength values higher than 66% of the base metal were achieved, thus giving ground for concrete industrial application.

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